INVESTIGATION OF THE PARTITIONING OF SOURCE AND RECEIVER-SITE FACTORS ON THE VARIANCE OF REGIONAL *P/S* AMPLITUDE RATIO DISCRIMINANTS

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ABSTRACT

In this project, we are investigating problems associated with applying regional-phase amplitude ratios, such as *Pn/Sn* or *Pn/Lg* ratios, for discrimination of explosions and earthquakes for monitoring the CTBT. Using multiple array recordings of groups of events in the same source region, the factors that contribute bias or the scatter of *P/S* ratio measurements after correction for path effects are characterized. These factors include both receiver site effects and source mechanism effects on *P/S* ratios. The study of site effects will be focused on arrays where we have seen site variations in *P/S* ratios, including the Scandinavian regional arrays (NORES, FINES, ARCES, FINES), and other new arrays in the International Monitoring System (IMS). The variance in the *P/S* ratio around regional arrays and large aperture arrays reveals the extent to which site affects cause variations in *P/S* ratios around different arrays in different regions. The partitioning of the variance between source, path, and receiver effects is examined by analysis of variance (ANOVA). We have performed an initial study of a group of presumed underwater explosions in the Gulf of Bothnia recorded by regional arrays in Scandinavia. We find that *P/S* and *P/S* amplitude ratios vary by as much as a factor of 3 around the FINES and NORES arrays, with apertures of 3 km, as well as similar variations for the different sources. These variations appear to be driven by variations in *Pn* and *Pg* amplitudes, whereas *Lg* amplitudes appear to be more stable. For source mechanism effects, we have been concentrating on earthquakes in the Zagros thrust belt of Western Iran, where, in a previous study, azimuthal variations in *P/S* ratios have been observed. Regional *P/S* ratios have been measured on these events and ANOVA is being used to determine to what extent the azimuthal variance can be partitioned between source effects, including focal mechanism and depth of focus, and propagation path effects. The results of this study will quantify the factors, other than propagation-path effects, that may bias the use of *P/S* ratios for seismic discrimination and provide a priori estimates of site variance for discrimination techniques.

KEY WORDS: discrimination, amplitude ratios, regional arrays, site effects, analysis-of-variance, underwater explosions

OBJECTIVE

The International Monitoring System (IMS) for the Comprehensive Test Ban Treaty (CTBT) faces the serious challenge of being able to accurately and reliably identify seismic events in any region of the world. This requirement extends to a very low magnitude threshold, mb=2.5, which is in the range of the sizes of local and regional seismic activity, both natural and artificial. Much research has been performed in recent years on developing discrimination techniques that classify seismic events into broad categories of source types, such as nuclear explosion, earthquake, and mine blast.

The seismic waveform discriminant which has been commonly investigated is the regional *P(Pn, Pg)/S(Sn, Lg)* amplitude ratio. Seismic source physics suggests that earthquakes, being dislocation sources, should be intrinsic sources of shear waves whereas explosions, being pure compressional sources, should only generate *P* waves. Therefore, explosions should have higher *P/S* amplitude ratios than earthquakes. This has been generally

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observed to be true, although the separation of explosions and earthquakes amplitude ratios is generally larger at high frequency (> 5 Hz) than at lower frequencies.

Observationally, nuclear explosions and earthquakes appear to be well separated by this discriminant (e.g., Baumgardt, 1993; Baumgardt and Der, 1994; Hartse et al., 1997). For example, Russian nuclear explosions observed at a Chinese station WMQ records no shear wave energy at frequencies above 6 Hz whereas Chinese earthquakes produce significant shear wave energy above 6 Hz. However, studies of mine blasts in Scandinavia and Germany (Baumgardt, 1993) indicate that many of the mine blasts seem to be intrinsic sources of shear waves, perhaps because they induce shear in fracturing and spallation in mines. Thus, low *P/S* ratios may be an indication of earthquakes, but many mine blasts may also have low values. However, we generally observe that most nuclear explosions will have high *P/S* ratios at high frequency compared to earthquakes, and mine blasts can also have high *P/S* ratios at high frequency.

Although *P/S* ratios appear to give promising discrimination between earthquakes and explosions, they have also been shown to have high degree of scatter which reduces the confidence of identification using such discrimination techniques as the outlier method (Fisk et al., 1996). Likely causes of this scatter includes the following:

1. <u>Propagation path effects</u> – These include differential attenuation of *P* and *S* and unmodeled propagation path effects, such as variations in elevation, crustal depth, and depth to basement (sediment thickness). Empirical studies of variations of *P/S* ratios with distance (e.g., Fisk et al, 1996) have resulted in distance corrections. Correlation studies for *P/S* amplitude ratios with crustal parameters (e.g., Zhang et al., 1994; Fan et al., 2001) have demonstrated that these correlations can reduce the variance of *P/S* ratios caused by unmodeled path effects.

2. <u>Source effects</u> – These may include ripple fire patterns in mine blasts, which can usually be identified by spectral techniques, magnitude differences (Xie and Patton, 1999; Ringdal et al., 2000), and possible differential radiation pattern effects on *P* and *S* amplitudes. The latter has usually been assumed to be small for high frequency regional waves. As mentioned above, mine blasts may also intrinsically excite shear waves to different degrees, depending on the local tectonic environment and the blasting practice, which can contribute high variance in *P/S* ratios. Finally, variations in depth of focus of earthquakes may also produce significant variations in *P/S* ratios.

3. <u>Site effects</u> – These include variations in *P* and *S* amplitudes caused by variations in the geology immediately below the site itself. These effects are usually local and not included in propagation-path corrections. Baumgardt and Der (1994) showed examples of site variance effects around the Iranian Long Period Array (ILPA) where both earthquake- and explosion-like *Pn/Lg* amplitude ratios were observed for sensors separated by several kilometers.

This paper addresses possible causes of scatter and bias in the use of regional *P/S* amplitude ratio discriminants that have not been much studied in previous research, although their importance has been noted. These effects may contribute to the residual variance in distributions of *P/S* ratios for earthquake populations even after the application of propagation-path corrections. These include of station site effects, perhaps due to variation in amplification of *P* and *S* waves by variable site geology, on the *P/S* ratios, as evidenced by the variation in *P/S* amplitude ratios around regional arrays. Also, earlier research (Baumgardt, 1996) has revealed that source radiation patterns from earthquakes in the Zagros mountains of western Iran, recorded at ILPA, may cause significant variation in *Pn*/*Lg* ratios. This study will follow up on that observation and investigate the effect in more detail to determine if the effect is due to source or propagation-path effects. Overall, this study will determine the likely maximum a priori variance that may be caused by these effects that may be useful in discrimination studies that must rely on single site measurements of regional *P/S* ratios.

<u>RESEARCH ACCOMPLISHED</u>

In this paper, we describe an initial study of site variances using regional arrays. Using multiple array recordings of groups of events in the same source region, the factors that contribute bias or the scatter of *P/S* ratio measurements are characterized. These factors include both receiver site effects and source effects on *P/S* ratios. The study of site effects will be focused on arrays where we have seen site variations in *P/S* ratios,

including the Scandinavian regional arrays (NORES, FINES, ARCES, FINES), and other new arrays in the International Monitoring System. The variance in the *P/S* ratio around regional arrays and large aperture arrays reveals the extent to which site affects cause variations in *P/S* ratios around different arrays in different regions.

Regional Array Recordings of Underwater Explosion Group in the Gulf of Bothnia

We have chosen as an initial study to analyze a group of events located in the Gulf of Bothnia that have been shown in a previous study (Baumgardt, 1999) to be several underwater explosions that occurred there in a single day on 18 May 1996. These events were discovered by searching the Reviewed Event Bulletin (REB) of the Prototype International Data Center (PIDC) for events located in offshore areas. The locations and the propagation paths to Scandinavian regional seismic arrays are shown in Figure 1. Baumgardt and Der (1998) previously discovered other events in the Gulf of Bothnia and showed that their spectral and cepstral characteristics were consistent with they're being underwater explosions. Baumgardt (1999) described a cepstral modeling and inversion approach for inferring the depth and yield of underwater explosions by inverting cepstra for underwater explosions. For the 18 May 1996 group of presumed underwater explosions, we found that the cepstra were very similar, and the resulting inversions gave very similar results. The yields ranged between 141 to 183 kg and depths from 69 to 72 m. These depths were consistent with the known bathymetric depths in the Gulf of Bothnia. There may have been some correlation between local magnitude and yield, since the cepstra for events with local magnitudes of 3.6 gave the higher yields of between 179 to 183 kg whereas the 3.4 to 3.5 events give yields between 141 and 165 g.

Figures 2 and 3 show a plots of the waveforms at the different array elements at FINES and NORES, respectively, from on of the 18 May 1996 events. The FINES array elements are between 304 and 306 km from the events, and *Pn* and *Pg* are difficult to separate there. NORES, on the other hand, at distances between 481 and 484, had clearly observable *Pn* and *Pg* phases. Both arrays recorded strong *Lg* waves from all the events. Figure 4 shows bandpass filtered waveforms recorded at the center elements of each array. These plots show that the range of frequencies for the highest signal-to-noise ratios is between 1.5 and 18 Hz for FINES and 1.5 and about 12 Hz for NORES. The peaking of the signal-to-noise ratios in the 2 to 4 Hz band at both arrays is due to the spectral modulations produced by the bubble pulse and surface reflections, discussed above.

Analysis of Site Variance of *P/S* and *P/S* Ratios

We measure the *P/S* and *P/S* ratios off of filtered waveform envelopes computed by calculating the RMS amplitudes in 1 second windows shifted down the traces. Figure 5 shows the array-stacked envelopes, called incoherent beams, with the phase picks shown. These same envelopes have been computed for each array element at NORES and FINES and the maximum phase amplitudes were measured in a 5 second window following the *Pn*, *Pg*, and *Lg* phase picks. *Pn*, *Pg*, and *Lg* amplitudes were determined in all the filter bands shown in Figures 4 and 5. *P/S* and *P/S* ratios were computed only when the signal-to-noise ratios exceeded 3. These measurements were made for 8 events in the Gulf of Bothnia.

Figure 7 shows examples of scatter plots of *P/S* ratios in the 3 to 6 Hz band at FINES and NORES array elements plotted versus the amplitudes of *Pn* and *Lg* for one of the events. These plots show that *P/S* amplitude ratios have a range of about .3 to .5 log units, or between a factor of 2 to 3. Moreover, the plots of *Pn/Lg* versus *Pn* amplitudes indicate higher correlation than those versus *Lg* amplitudes. This indicates that the *Pn* amplitude variations around both FINES and NORES control the *Pn/Lg* amplitude variations.

To explore this more rigorously, we apply a two-way analysis of variance (ANOVA2) test for the variation in the amplitudes of *Pn*, *Pg*, and *Lg* and the amplitude ratios of *Pn/Lg* and *Pg/ Lg* for the 7 Gulf of Bothnia events. In ANOVA2, we fit the following model to the amplitudes and amplitude ratios:

$$y_{ijk} = \mu + \alpha_{,j} + \beta_{i,} + \varepsilon_{ijk}$$

where y_{ijk} are the array element amplitudes or amplitude ratios, μ is the mean of all the data, $\alpha_{,j}$ is the source term, $\beta_{i,}$ is the site term, and ε_{ijk} is the error term. This model is fit to the logarithms of amplitudes and amplitude ratios where it is assumed that the amplitudes and ratios are log-normal and dependent on both the additive event and the site effects both of which are specified to have a zero sum. The errors are assumed to be normally distributed. ANOVA2 in essence tests the hypothesis that the data come from the same population

with a common mean (Johnson and Wichern, 1988). In this study, we focus on the variations in the site terms and ignore for the time being the significance tests on the commonality of the mean.

Figure 7 shows the configurations of the FINES and NORES arrays with color-coding for the different array elements, grouped by rings. Figure 8 shows the site terms for NORES in the 2-4 Hz, 3-6 Hz, and 4.9 to 9 Hz frequency bands obtained by this analysis for *Pn/Lg* amplitude ratios and *Pn* and *Lg* amplitudes. The histograms refer to the site term values for the different array elements in the rings color-coded as in Figure 7. These plots show that the greatest variability in *Pn/Lg* ratios occurs for the NORES sensors that have the greatest spatial separation or aperture, i.e, rings C and D. The *Pn* phase also has correspondingly large systematic variation that is largest for the sensors in the rings with the largest aperture. The *Lg* site terms are relatively small, except for the 4.5 to 9 Hz band, and essentially independent of the separation of the sensors. The same result resulted for the *Pg/Lg* amplitude ratios, and *Pg* and *Lg* amplitudes at NORES shown in Figure 9. Finally, Figure 10 shows the variation in site terms for the *Pn/Lg* ratios at FINES. These again show the same systematic variations. The source terms had similar variation, which is on the order of 0.3 to 0.5 in the log of the *Pn/Lg* and *Pg/Lg* amplitude ratios.

CONCLUSIONS AND RECOMMENDATIONS

This paper has described a method for analyzing site variance in regional *P/S* ratios and a preliminary application to data recorded by Scandinavian regional arrays for a group of underwater explosions in the same location. We have found that the amplitude ratios *Pn/Lg* and *Pg/Lg* varied by between a factor of 2 to 3 around the elements of both NORES and FINES regional arrays in all the frequency bands with signal-to-noise ratios in excess of 3. This variation, which occurs only over a spatial aperture of 3 km for both arrays, appears to be systematic, with the largest variations between sensors with the largest separation, which is up to 3 km, and correlates more strongly with *Pn* and *Pg* amplitudes than with *Lg* amplitudes. *Lg* appears to be more stable than *Pn*, and *Pg*, or less sensitive to site effects, except perhaps in the higher frequency bands, where stronger but more random variations in *Lg* site terms are observed.

In this project, we will apply this same analysis for other groups for events, including mine blasts and earthquake groups, and investigate if these same kinds of variations occur for other source types. Also, this same analysis will be applied to arrays in other regions, including more tectonically active regions than the Scandinavian shield region.

For source mechanism effects, we have been concentrating on earthquakes in the Zagros thrust belt of Western Iran, where, in a previous study (Baumgardt, 1996), azimuthal variations in *P/S* ratios have been observed. In that study, we speculated that variations may be explained by the predominantly thrust mechanism of the earthquakes in the Zagros, but only a limited number of waveforms were examined. For this study, an extensive database of waveforms of regional recordings of Zagros events of different magnitudes and depths has been collected. Regional *P/S* ratios have been measured on these events and ANOVA is being used to determine to what extent the azimuthal variance can be partitioned between source effects, including focal mechanism and depth of focus, and propagation path effects. The results of this study will quantify the factors, other than propagation-path effects, that may bias the use of *P/S* ratios for seismic discrimination.

REFERENCES

Baumgardt, D.R. (1993). Regional characterization of mine blasts, earthquakes, mine tremors, and nuclear explosions using the Intelligent Event Identification System, Final Report to ARPA, SAS-TR-94-12, ENSCO, Inc., Springfield, VA.

Baumgardt, D.R. and Z. Der (1995). Investigation of the transportability of the *P/S* ratio discriminant to different tectonic regions, Scientific Report No. 1, *PL-TR-94-2299*, 6 December 1994, ENSCO, Inc.

Baumgardt, D.R. (1996). Investigation of *Lg* blockage and the transportability of regional discriminants in the Middle East, *Scientific Report No. 1*, *Pl-TR-96-2294*, ENSCO, Inc., Springfield, VA.

Baumgardt, D.R. (1999). Characterization of underwater explosions by spectral/cepstral analysis, modeling, and inversion, Annual Report submitted to DTRA, November, 1999, ENSCO, Inc., Springfield, VA.

Baumgardt, D.R. and Z. Der (1995). Investigation of the transportability of the *P/S* ratio discriminant to different tectonic regions, Scientific Report No. 1, *PL-TR-94-2299*, 6 December 1994, ENSCO, Inc.

Baumgardt, D.R. and Z. Der (1998). Identification of presumed shallow underwater chemical explosions using land-based regional arrays, *Bull. Seism. Soc. Am.* , **88**, 581-595.

Fan, G-W., T. Lay, and S. Bottone (2001). Path corrections for source discriminants: a case study of two International Seismic Monitoring stations, submitted to *Pure and Applied Geophys.*

Fisk, M., H.L. Gray, and G.D. McCartor (1996). Regional event discrimination without transporting thresholds, *Bull. Seism. Soc. Am.*, 1545-1558.

Hartse, H.E., S.R. Taylor, W.S. Phillips, and G.E. Randall (1997). Regional event discrimination in central Asia with emphasis on western China, *Bull. Seism. Soc. Am.*, **87**, 551-568.

Johnson, A, .and D.W. Wichern (1988). *Applied Multivariate Statistical Analysis*, Prentice Hall, Englewood Cliffs, New Jersey.

Ringdal, F., E. Kremenetskaya and V. Asming (2000). Observed characteristics of regional seismic phases and implications for *P/S* discrimination in the European Arctic, submitted to *PAGEOPH Special Issue on CTBT Monitoring*.

Xie, J. and H. Patton (1999). Regional phase excitation and propagation in the Lop Nor region of Central Asia and implications for the physical basis of *P/Lg* discriminants, *J. Geophys. Res.*, **104**, 941-954.

Zhang, T., S.Y. Schwartz, and T. Lay (1994). Multivariate analysis of waveguide effects on short-period regional wave propagation in Eurasia and its application in seismic discrimination, *J. Geophys. Res.*, **99**, 21929-21945.

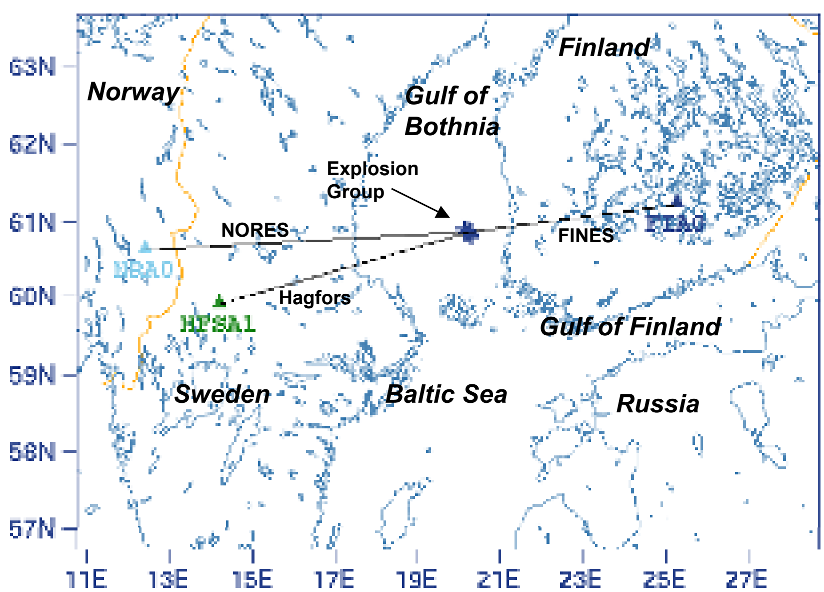

Figure 1. Map showing location of presumed underwater explosions recorded by the three seismic arrays in Scandinavia, NORES, FINES, and Hagfors.

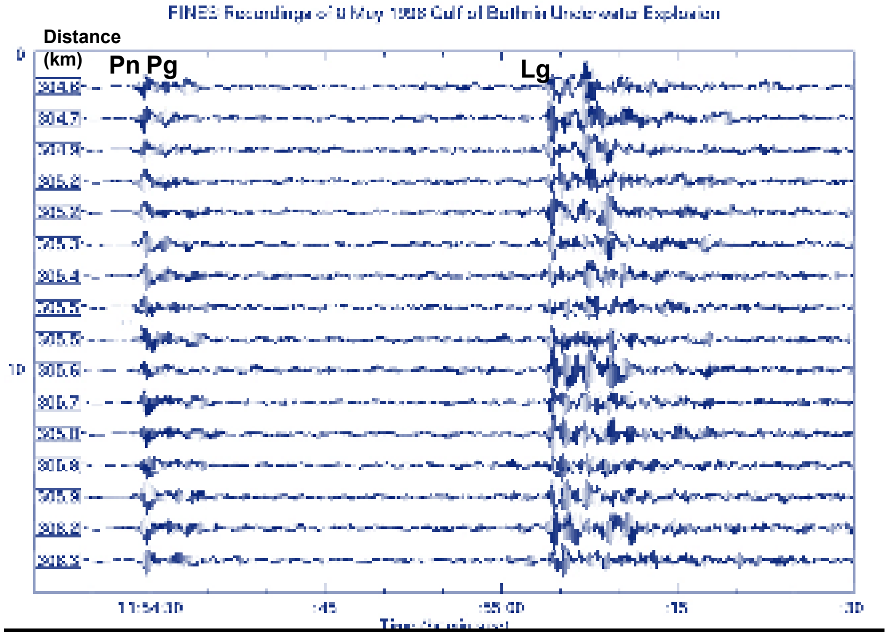

Figure 2: Waveforms recorded at FINES from one of the underwater explosions in the Gulf of Bothnia.

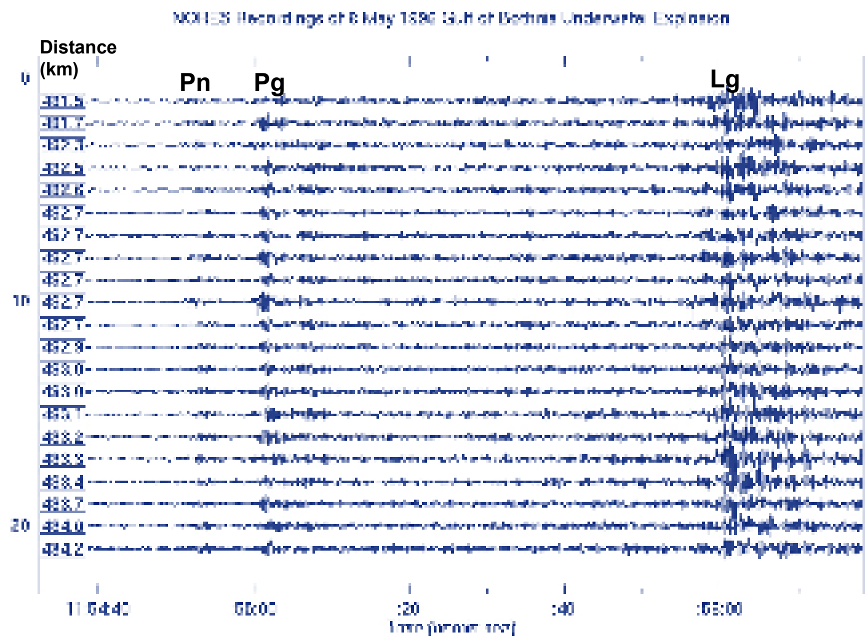

Figure 3: Waveforms recorded at NORES from one of the underwater explosions in the Gulf of Bothnia.

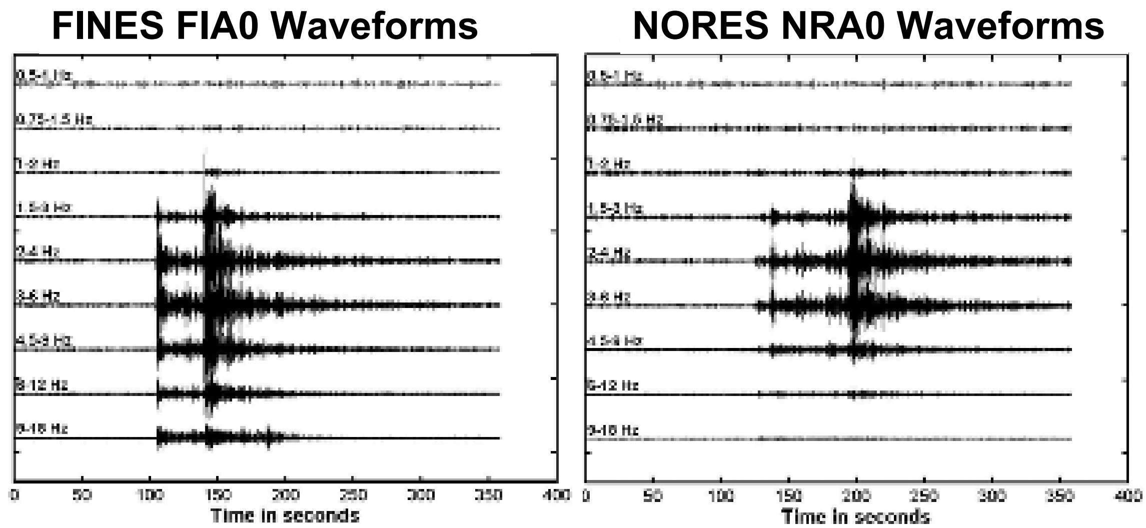

Figure 4: Bandpass filtered waveforms recorded at the center elements of the FINES arrays (left) and the NORES array (right) from one of the Gulf of Bothnia explosions.

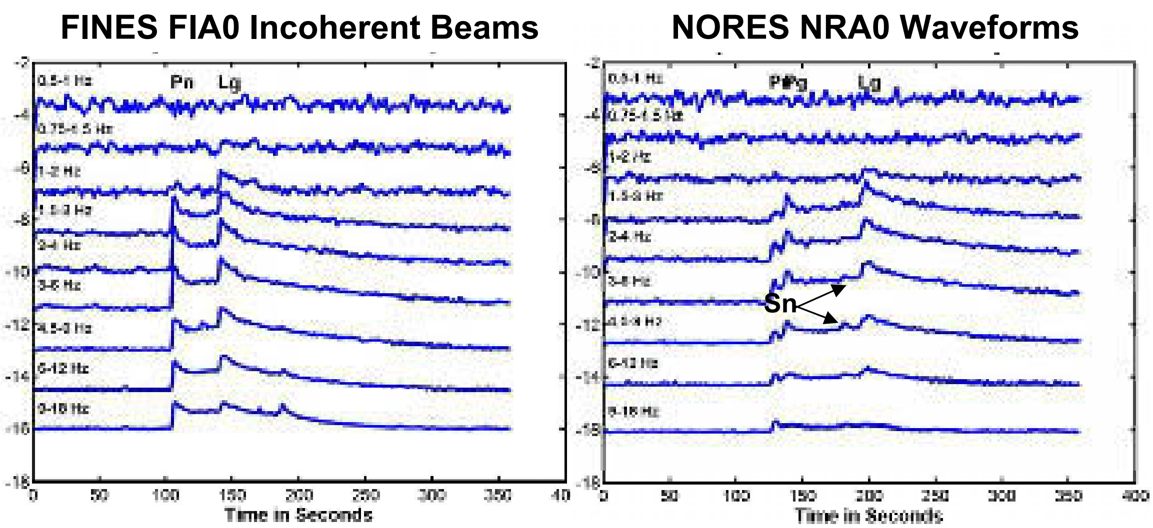

Figure 5: Log RMS incoherent beam plots of the filtered waveforms for FINES (left) and NORES (waveforms). Regional phases picked on waveforms are indicated at the top. Amplitudes of phases are measured off maximum values of RMS envelop plots of each channel and on incoherent beams.

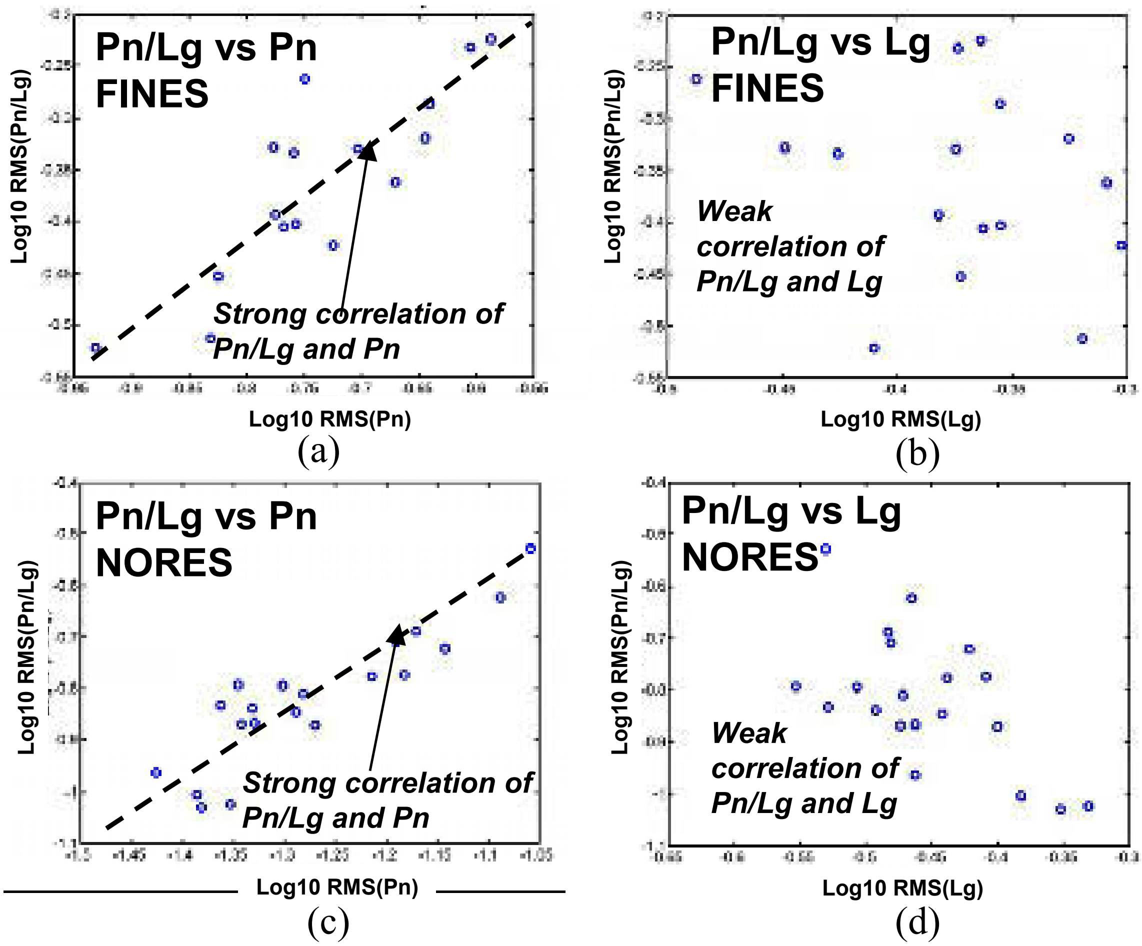

Figure 6: Scatter plots of the *Pn/Lg* ratios versus *Pn* and *Lg* amplitudes in the 3 to 6 Hz frequency band for the regional arrays for one of the Gulf of Bothnia underwater blasts. (a), (b) Scatter plots for FINES. (c), (d) Scatter plots for NORES.

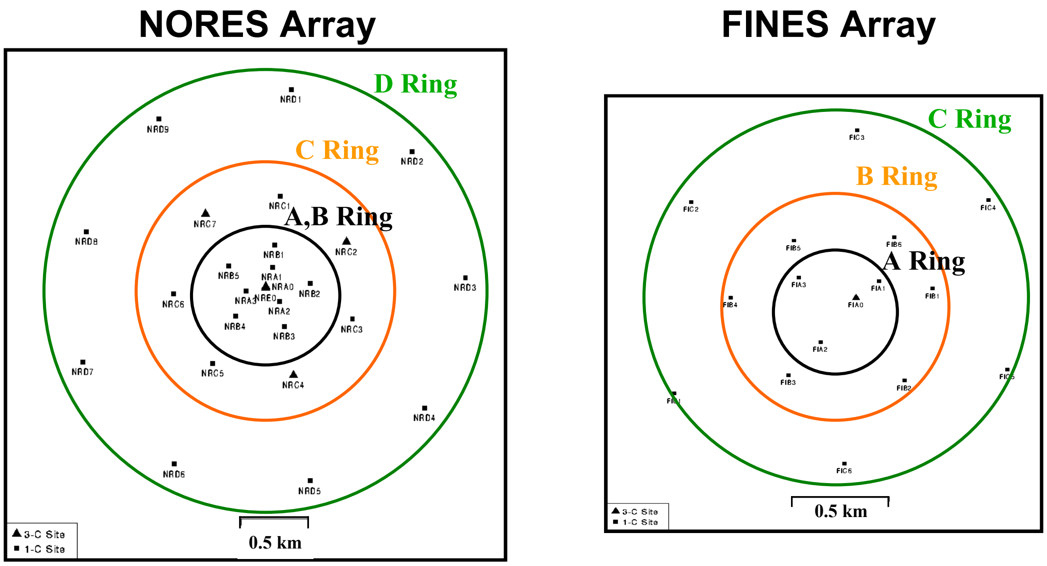

Figure 7: Site layouts for the NORES (left) and FINES array. Colors green, red, and black refer to large, medium, and small aperture rings, respectively, for the arrays.

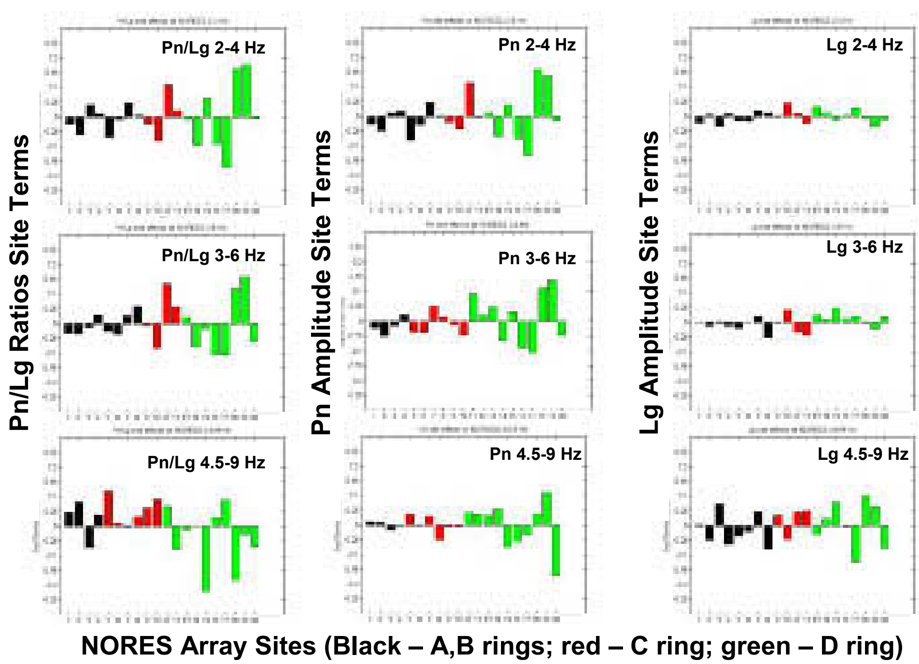

Figure 8: ANOVA2 path terms for *Pn/Lg* amplitude ratios, *Pn* and *Lg* amplitudes for NORES in three frequency bands.

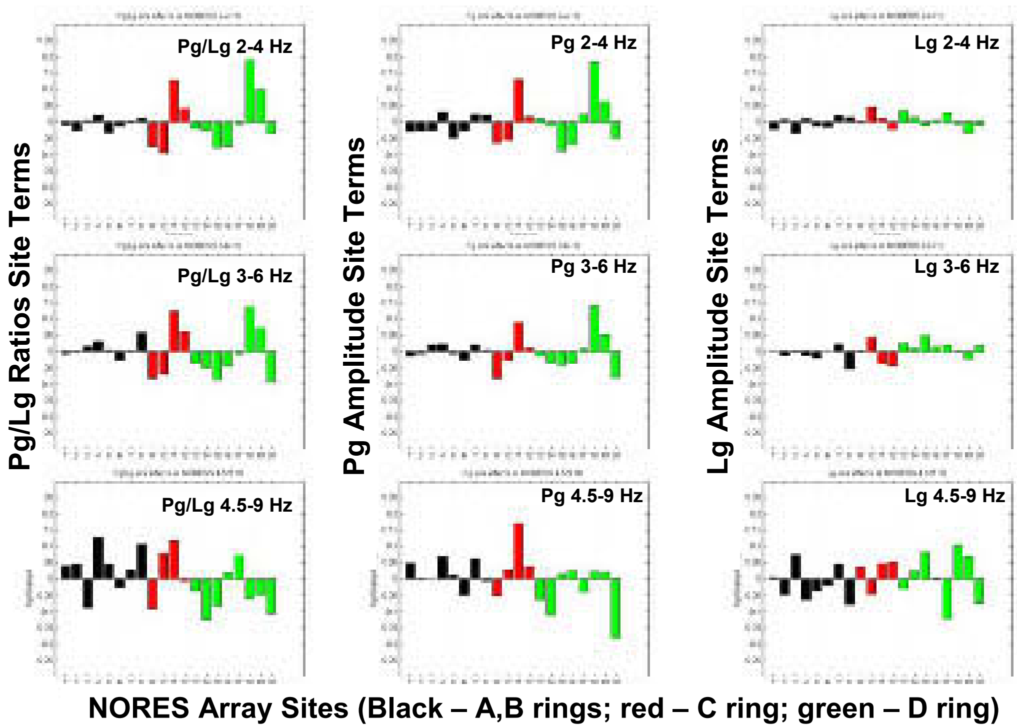

Figure 9: ANOVA2 path terms for *Pg/Lg* amplitude ratios, *Pg* and *Lg* amplitudes for NORES in three frequency bands.

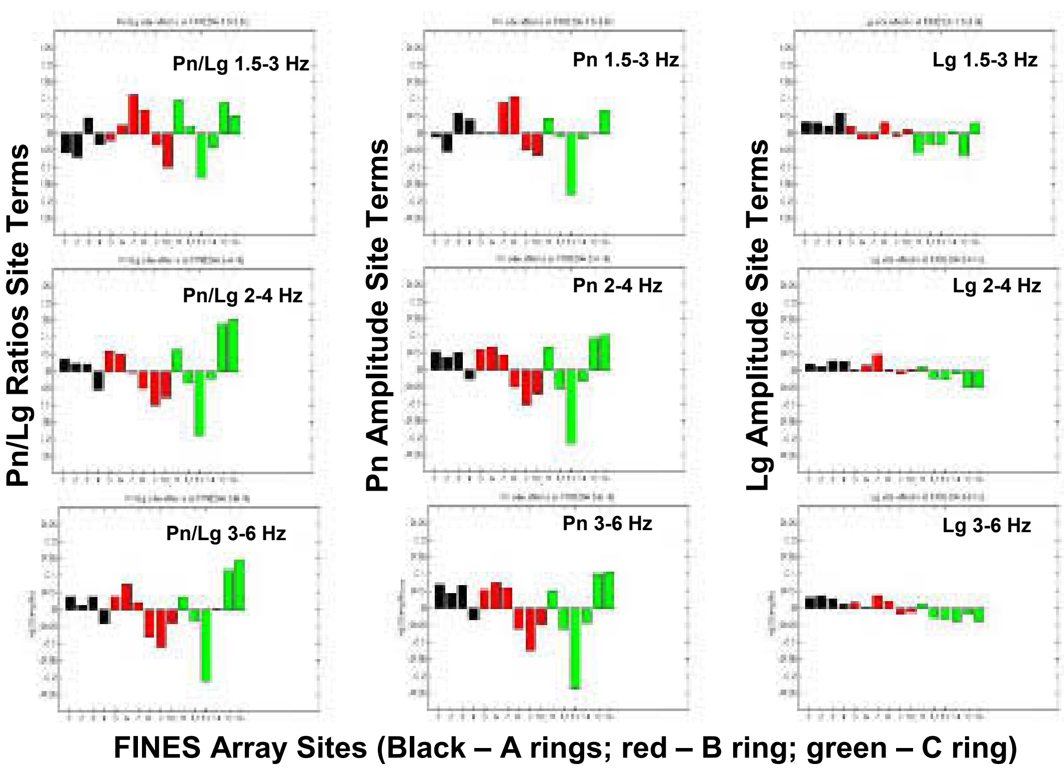

Figure 10: ANOVA2 path terms for *Pn/Lg* amplitude ratios, *Pn* and *Lg* amplitudes for FINES in three frequency bands